THE SIZE OF ANTIMATTER BODIES AND THE PRIMARY COSMIC RAY FLUX

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ABSTRACT

The consequences of antimatter bodies on the very high energy primary cosmic ray flux are considered. The effects of various models of cosmic ray origin and properties of astrophysical parameters are discussed. A simple expression for the production of antiprotons in N-N collisions as a function of energy of the incident proton is obtained by utilizing characteristics of particles produced in high energy collisions. It is assumed that sufficient time will have elasped for all antibaryons to decay to antiprotons.

INTRODUCTION

The symmetry between particles and antiparticles that have been observed upon earth has led to the hypothesis that the universe should contain not only matter but also antimatter[1,2,3,4,5,6,7,8]. Recently Harrison[4] has proposed Baryon inhomogeneities in the early stages of the formation of the universe which could account for the formation of "antigalaxies."

Out of the multitude of questions that arises from these investigations, one is, "What size are the antimatter bodies?" One would expect that they are not smaller than the size of our galaxy, otherwise we would probably see antimatter in the primary cosmic ray flux at low energies ($10 \text{ GeV} < E < 10^6 \text{ GeV}$). But are the bodies then of the size of a galaxy or even much larger? We will indicate some of the possible effects that various sizes might have on the primary cosmic ray flux.

SIZE EFFECTS

The observed primary cosmic ray spectrum has a break (ankle) at $E_a \approx 10^7 - 10^8$ GeV. The usual interpretation of this break in the spectrum is that particles with energies less than E_a are of galactic origin and that those with energies greater than E_a are particles that have escaped from neighboring galaxies. If we assume that the antimatter bodies are of the size of a galaxy we would expect, barring other sources (see section III), the primary cosmic rays of energy greater than E_a to contain antimatter in proportion to the ratio, R, of antimatter to matter bodies. Thus if $R \simeq 1$ the cosmic ray flux with $E > E_a$ would be about 1/2 antimatter.

Let us assume that extragalactic cosmic rays are governed by diffusion processes and are confined to the region of intergalactic space for 10^{10} yrs. with a mean free path of 10^5 l.y. One can estimate the region in which they remain to have a radius of approximately $3x10^7$ l.y.[9] (the local metagalactic model).

CONTAMINATIONS

We now examine the various contaminations that could affect the antimatter flux. The first one that we will consider is of antiprotons which are produced within our galaxy. Wayland and Bowen[10] have shown the antiproton flux which should arise from production, acceleration, and diffusion within our galaxy is as in Fig. I. Thus the very high energy spectrum will not be seriously affected by locally produced antiprotons. Note that even those antiprotons which escape are down by a factor of 10^{-5} and would not mask the component for an antimatter to matter ratio of 10^{-3}.

A second possibility is the production of antiprotons in intergalactic space when cosmic ray protons collide with intergalactic protons. We can estimate this flux, J, by noting

$$J = cn = c\bar{q}\tau_{eff} \tag{1}$$

where

n = number density of antiprotons ($\bar{p}/cm^3 sr.$)

$\bar{q}$ = production rate of antiprotons ($\bar{p}/cm^3 sec.sr.$)

τ_{eff} = the effective life time (sec.)

We can approximate $\bar{q}$ by

$$\bar{q} = \int_{E_a}^{\infty} \rho\sigma j(E)dE \approx \rho\bar{\sigma}J(E_a), \tag{2}$$

where j(E)dE is the differential and J(E) the integral energy spectrum of primary cosmic rays, ρ is the density of matter in intergalactic space and $\bar{\sigma}$ is the average production cross section in the energy range greater than E_a. This can be estimated from the formula (see appendix)

$$\sigma_{\bar{p}} = 0.775 \; (E_o^{1/4} - 2.5) \qquad (3)$$

where E_o is the energy of the incident proton. In the energy range greater than E_a this is approximately 100 mb. We take the value of $J(E_a)$ from the measured cosmic ray integral flux to be 10^{-13}(#/cm^{2}sec. sr.) and take $\rho \approx 10^{-6}$ (#/cm^3)[11]. Thus $\bar{q} \approx 10^{-44}$ ($\bar{p}$/cm^{3}sec.sr.). Recall that $\tau_{eff}^{-1} = \tau_{ann}^{-1} + \tau_{esc}^{-1}$ where τ_{ann} is the annihilation life time for $\bar{p}$ and τ_{esc} is the escape lifetime. The Pomeranchuk theorem[12] says that at very high energies, particle and antiparticle cross sections tend to be equal and of constant finite values. As an approximate estimate we will take $\sigma_{\bar{p}p} \approx \sigma_{pp} \approx 40$mb. We have used the value for σ_{pp} given by Diddens, et al.[13] Then $\tau_{ann} \approx (\rho c \sigma_{\bar{p}p})^{-1} \approx 8.3\text{x}10^{20}$sec. $\approx 2.6\text{x}10^{13}$yrs. This is, of course, many times the age of the universe and we can set $\tau_{eff} \approx \tau_{esc} \approx 10^{10}$yrs. We calculate J from Eqn. (1) to find that it is $9\text{x}10^{-17}$ ($\bar{p}$/cm^{2}sec.sr.) at $E_a \approx 10^7$ GeV. Thus we can neglect the production of antiprotons in intergalactic space obscuring the antimatter flux.

A third consideration is the removal of the antimatter flux by interactions with the intergalactic medium. The intergalactic medium could, under the conditions of a balance of matter to antimatter, be composed not only of matter but also of antimatter. Gould and Burbidge[14] have shown that the upper limits of the γ ray flux in cosmic rays implies that either the matter and antimatter are separated or that the ratio of antimatter to matter is less than 10^{-6}. We shall assume that they are separated. Antimatter - antimatter collisions would not remove the antimatter flux. As we saw above, the annihilation of antimatter on matter would take approximately $2.6\text{x}10^{13}$ yrs.[†]

[†]We have used the results of antiproton cross sections to obtain an estimate for antimatter annihilation cross sections.

This is too long to be an effective removal agent.

Another factor that could affect the antimatter flux would be its interaction with the interstellar matter of our galaxy. At the energies greater than E_a the cosmic ray particles would travel in approximately a straight line. At most, then, the total path length would be the diameter of our galaxy ($\sim$25kpc) and thus would spend about $8x10^4$ yrs. in traversing matter of a higher density ($\sim 10^{-2}/cm^3$). But, using the above cross section for annihilation, we find that $\tau_{ann} \approx 2x10^9$ yrs.* Again, the effect on the antimatter flux can be neglected.

*If the density is increased to $1/cm^3$, we find that $\tau_{ann} \approx 2x10^7$ yrs.

DISCUSSION AND CONCLUSION

In the above computation we have made assumptions that should be stated explicitly. When we choose ρ(intergalactic) $\simeq 10^{-6}/cm^3$ we took a mean value without consideration of cosmological theories of the origin of the universe. This value of the density could vary by a factor of 100 higher and not appreciably change our results. Also we have assumed a diffusion theory in our calculation of $\bar{p}$ production in intergalactic space. Burbidge[15] has suggested that the extragalactic cosmic rays come from strong radio sources. Even if there is no diffusion and the extragalactic cosmic ray particles travel in straight lines, the above considerations indicate that we would still expect a similar situation as outlined above. (In this case the sampling region approaches the size of the observable universe). However, if the extragalactic cosmic ray sources are the result of matter-antimatter explosions one would have to alter the above conclusions. Considerations of this type are beyond the scope of this note.

The attempts to observe antimatter in cosmic rays have been at low energies and without success[16,17,18,19]. Existing experimental techniques will not distinguish between matter and antimatter cosmic ray fluxes at energies as great as E_a.

In conclusion, we note that in the energy range greater than 10^7 - 10^8 GeV that the presence of an appreciable antimatter flux in the primary cosmic ray flux indicates the antimatter bodies are probably of the size of a galaxy.† If extragalactic cosmic rays diffuse within the supercluster, the lack of an appreciable very high energy antimatter flux could indicate that either the antimatter bodies are farther away than $3x10^7$ l.y. (and probably of that size or greater) or that the ratio of antimatter to matter bodies within $3x10^7$ l.y. is very low.

† if we assume extragalactic diffusion.

APPENDIX

Antiproton Production at High Energies

For the case of production at $\gtrsim$ 100 GeV, we define the following:

$$
\begin{aligned}
n_{\pi^0} &= \text{average number of } \pi^0 \text{ produced,} \\
n_{x^0} &= \text{average number of neutral particles heavier than } \pi\text{'s produced,} \\
n_{x^\pm} &= \text{average number of charged particles heavier than } \pi\text{'s produced,} \\
n_{\pi^\pm} &= \text{average number of } \pi^\pm \text{ produced,} \\
n_{\pm} &= \text{average number of all charged particles produced,} \\
n_{x} &= \text{average number of all x particles produced,} \\
n &= \text{average number of all particles produced.}
\end{aligned}
\tag{A1}
$$

Then by definition we have

$$n_\pm = n_{\pi^\pm} + n_{x^\pm}, \tag{A2}$$

$$n_x = n_{x^0} + n_{x^\pm}, \tag{A3}$$

$$n = n_\pm + n_{x^0} + n_{\pi^0}. \tag{A4}$$

From Eqn. (A2) we find

$$\frac{n_{x^\pm}}{n_\pm} = 1 - \frac{n_{\pi^\pm}}{n_\pm} = 1 - 2\frac{n_{\pi^0}}{n_\pm} = 1 - 2R, \tag{A5}$$

where we have assumed that $n_{\pi^\pm} = 2n_{\pi^0}$, and defined

$$R \equiv \frac{n_{\pi^0}}{n_\pm} = \frac{n_{\pi^0}}{n_{\pi^\pm} + n_{x^\pm}} \tag{A6}$$

Now consider Eqns. (A3) and (A4)

$$\frac{n_x}{n} = \frac{n_{x^\pm}\left(\frac{n_{x^0}}{n_{x^\pm}} + 1\right)}{n_\pm\left(1 + \frac{n_{x^0}}{n_\pm} + \frac{n_{\pi^0}}{n_\pm}\right)}. \tag{A7}$$

We know experimentally that $n_{x^0} \approx n_{x^\pm}$ [20] and from Eqn. (A5),

$$\frac{n_{\pi^0}}{n_\pm} = 1/2\left(1 - \frac{n_{x^\pm}}{n_\pm}\right),$$

so we can write Eqn. (A7) as

$$\frac{n_x}{n} = \frac{2(1 - 2R)}{2 - R} \tag{A8}$$

If we assume from the statistical model the usual form[20] of $n = a + bE_o^{1/4}$ (where E_o is the energy of the incident particle) Eqn. (A8) can be written as:

$$n_x = \frac{2(1 - 2R)}{2 - R} (a + bE_o^{1/4}). \tag{A9}$$

If one examines the possible production reactions for x particles in N-N collisions[20], one notices that

$$n_x \simeq 2 + 2n_{\bar{x}}, \tag{A10}$$

where $n_{\bar{x}}$ is the average number of anti -x particles. Then we have

$$n_{\bar{x}} \simeq \left[\frac{2(1 - 2R)}{2 - R} \right] \left[\frac{a + bE_o^{1/4}}{2} \right] - 1. \tag{A11}$$

Note that $a \simeq 0$ and $b \simeq 3.2$[20]. For a large energy range it is known that $R \simeq 0.4$. This ratio is found from counting the number of positron-electron pairs formed. If we weigh the possible reactions by the method of Yelvin and De Shalit[21], and Barasenkov and Barbasev[22] (using the possible decay states and branching ratios given in the tabulation of Rosenfeld, et al.[23]) it is found that the error from not including other sources (i.e., other than π^o) of γ's is less than 3%. Thus Eqn. (11) becomes

$$n_{\bar{x}} \simeq 0.4E_o^{1/4} - 1. \tag{A12}$$

If we assume that enough time has passed for all $\bar{Y}$ to decay into $\bar{p}$ we can write (as an equivalent condition)

$$n_{\bar{x}} = n_{\bar{K}} + n_{\bar{p}}. \tag{A13}$$

as $n_{\bar{K}^o} \simeq n_{K^-}$ (20)

$$n_{\bar{x}} \simeq n_{\bar{p}} \left(1 + \frac{2n_{K^-}}{n_{\bar{p}}}\right). \tag{A14}$$

Particle production in N-N collisions[24,25] have the interesting characteristic that the momentum spectra of K^- and $\bar{p}$ have almost the same shape. Using the results of experiment[20,24,25] we find $n_{\bar{p}}/n_{\bar{K}} \approx 0.125$. Thus

$$n_{\bar{x}} \approx 17 n_{\bar{p}}. \tag{A15}$$

Using Eqns. (A12) and (A15) we have

$$n_{\bar{p}} \approx 0.025\ (E_o^{1/4} - 2.5) \tag{A16}$$

The average number of produced heavy antiparticles is

$$n_{\bar{H}} = \sum_i n_{\bar{H}_i}\ W_i = \frac{\sum_i \sigma_{\bar{H}_i}}{\sigma_{in}} \tag{A17}$$

where W_i is the probability of the i^{th} interaction in the inelastic reactions and $\sigma_{in} \approx 31$ mb over a large energy range[26]. As an approximation we will assume that $\sigma_{in} \approx 31$mb. Thus,

$$\sigma_{\bar{p}} \approx 0.775\ (E_o^{1/4} - 2.5) \tag{A18}$$

for E_o in GeV and $\sigma_{\bar{p}}$ in mb. A plot of $\sigma_{\bar{p}}$ vs. E_o is shown in Fig. II.

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REFERENCES

[1]M. Goldhaber, Science 124, 218 (1958)

[2]H. Alfven and O. Klein, Arkiv Fysik 23, 187 (1962)

[3]H. Alfven, Rev. Mod. Phys. 37, 652 (1965)

[4]E. R. Harrison, Phy. Rev. Lett. 18, 1011 (1967)

[5]F. Hoyle and J. V. Narlikar, Proc. Royal Soc., A290, 143 (1966)

[6]P. Morrison, Am. J. Phys. 26, 358 (1958)

[7]G. R. Burbidge and F. Hoyle, Nuovo Cimento 4, 558 (1956)

[8]H. Y. Chiu, Phys. Rev. Lett. 17, 712 (1966)

[9]H. Laster, Phys. Rev. 135, B1274 (1964)

[10]J. R. Wayland and T. Bowen (to be published)

[11]C. W. Allen, Astrophysical Quantities (2nd Ed.), University of London Press, 1963

[12]I. Y. Pomeranchuk, JETP 7, 499 (1958)

[13]A. N. Diddens, et al., Phys. Rev. Lett. 9, 32 (1962)

[14]R. J. Gould and G. R. Burbidge, Handbuch der Physik ed. by S. Flügge (Springer - Verlag, 1967), Vol. 46/2, p. 284

[15]G. Burbidge, Prog. Theo. Phys. (Koyto) 27, 999 (1962)

[16]D. M. Haskin, et al., Proc. Moscow Cosmic Ray Conf., 3, 123 (1960)

[17]K. Aizu, et al., Phys. Rev. 121, 1206 (1961)

[18]N. L. Grigorov, et al., Artificial Earth Satellites 9, 232 (1962)

[19]M. V. K. Apparao, TIFR 67-5 (unpublished)

[20]V. S. Barashenkov, V. M. Mal'tser and I. Patera, Fortsch. der Phy. 14, 357 (1966)

[21]Y. Yelvin and A. De Shalit, Nuovo Cimento 1, 1147 (1955)

[22]V. S. Barashenkov and B. M. Barbasev, Suppl. Nuovo Cimento 1, 19 (1958)

[23]A. H. Rosenfeld, et al., Reviews Modern Physics 39, 1 (1967)

[24]W. F. Baker, et al., Phys. Rev. Lett. 7, 101 (1961)

[25]D. Dekkers, et al., Phys. Rev. 137, B962 (1965)

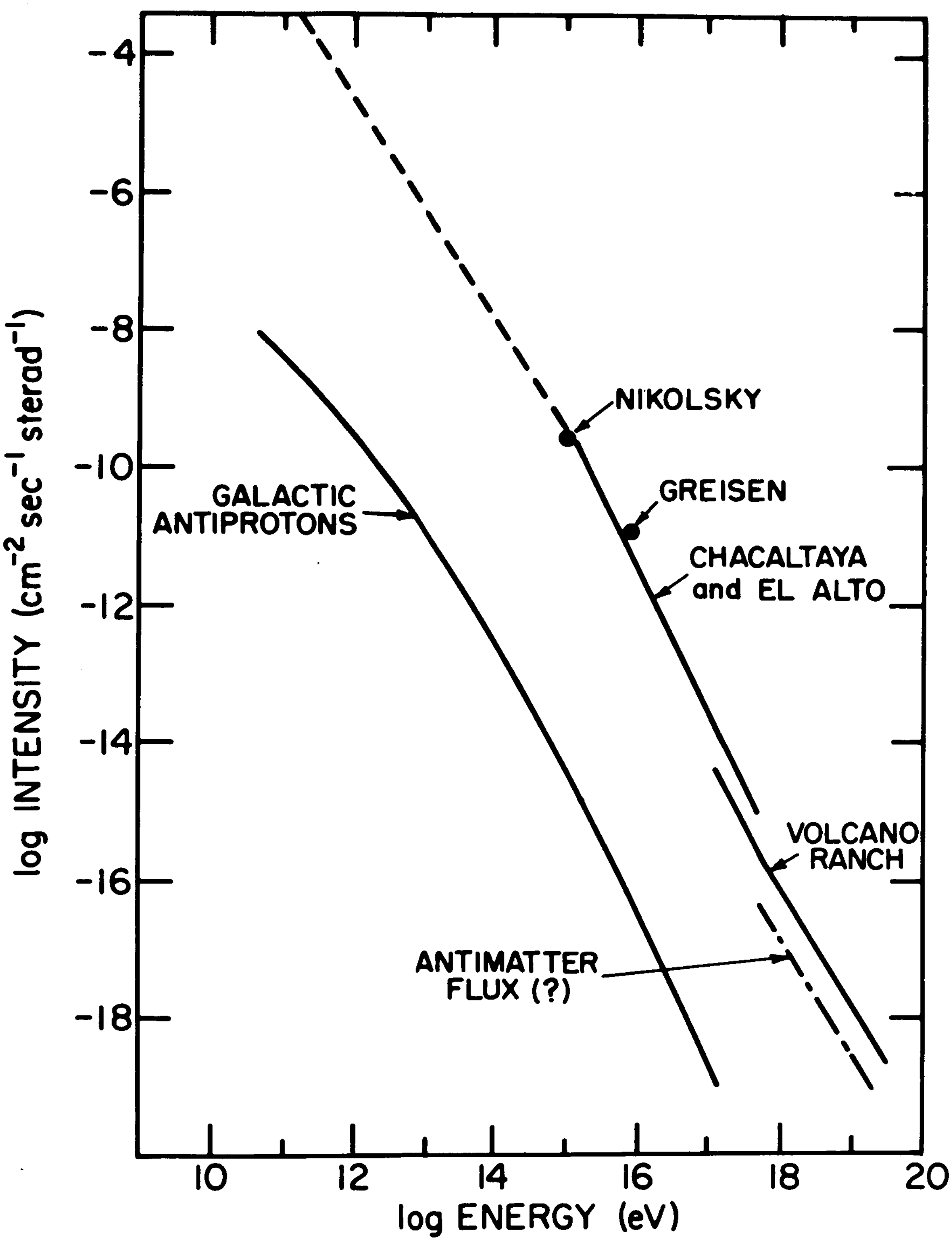

Fig. 1. COSMIC RAY FLUX.

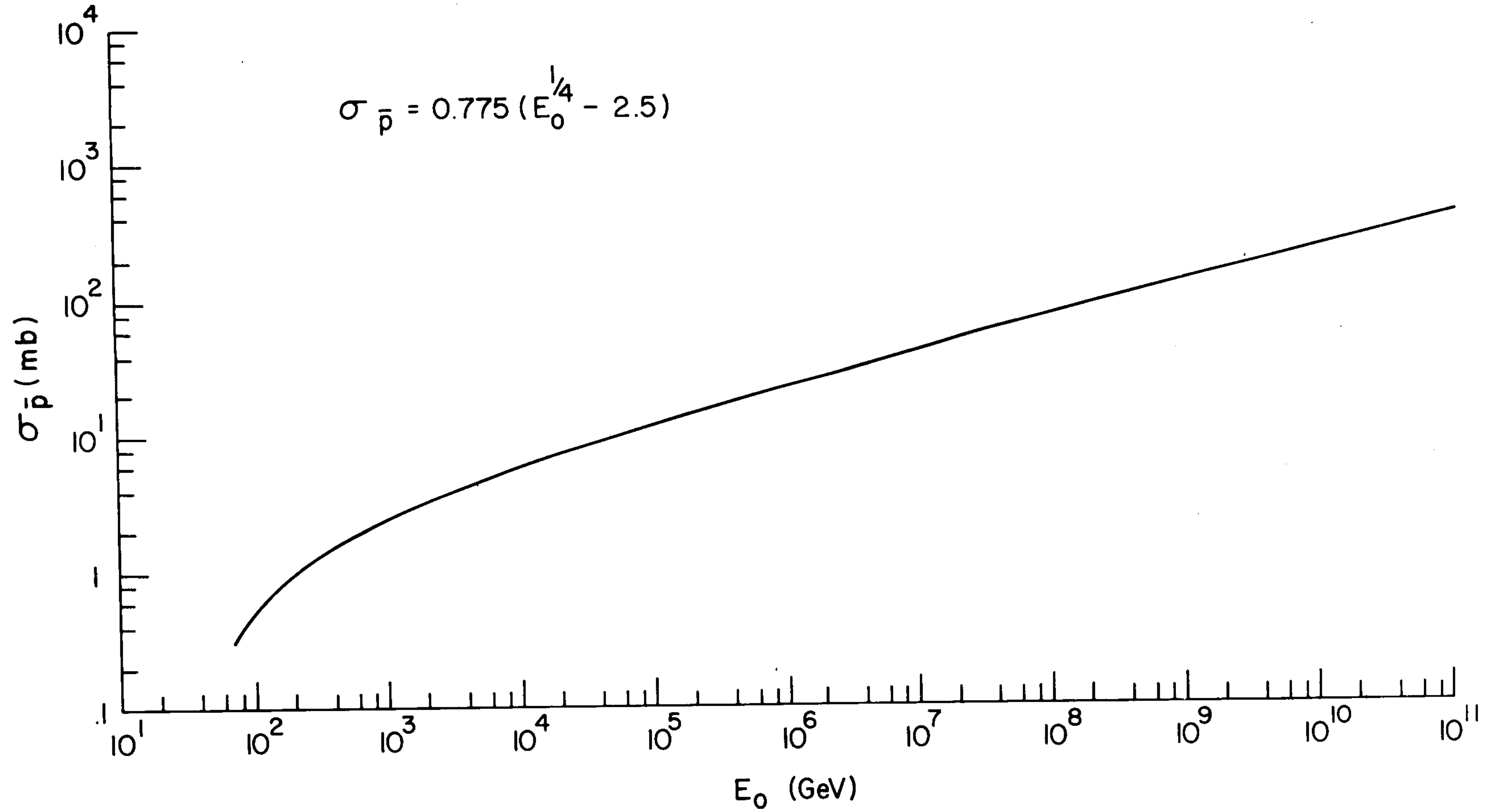

Fig.2 ANTIPROTON PRODUCTION CROSS SECTION, $\sigma_{\bar{p}}$, AS A FUNCTION OF INCIDENT ENERGY, E_0.